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A Problem of Stand-off Energy Sources for MTF

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Fusion devices based on the adiabatic (or shock) compression of the plasma by electromagnetically driven liner need specific energy sources capable of delivering a high current (~10 MA) in the pulses 0.1 - 1 microsecond long. In the present experimental facilities, the plasma load is situated very close to the pulse-power energy source. In the future fusion devices, one would have to place a plasma load at a considerable distance from the energy source (to avoid strong neutron and thermo-mechanical damage to the source). Several versions of the stand-off energy sources are considered. All are based on the idea of an "assembly" - an object where the plasma load is nested and which contains all necessary circuitry that allows conversion of the energy delivered to the assembly into the magnetic energy. Such "assemblies" will be dropped (or inserted) into the reaction chamber at a desired rate and energized by a stand-off energy source. Four specific concepts have been mentioned.

A concept of Magnetized Target Fusion (MTF) is very broad, encompassing fusion systems with the yields from many gigajoules per pulse [1, 2] to a few megajoules per pulse [3]. The repetition rate may also vary in a broad range, from ~0.1 s^{-1} (for high-yield systems) to ~ 20 s^{-1} (for low-yield systems). A common problem in all this variety of systems is a need in protecting the primary energy source from a neutron and thermo-mechanical damage associated with fusion energy release. The means to reach this goal may differ considerably depending on the yield and the repetition rate. We will briefly discuss here possible solutions for low-yield, high rep-rate systems. It should be noted that the problem of stand-off energy sources is still in its infancy, and there are no detailed analyses available. The aim of this paper is merely to show that, at least at the level of basic physical principles, stand-off energy sources are feasible.

To be more specific, we discuss a version of MTF based on the use of a field-reversed configuration (FRC), although the use of other magnetic configurations (spheromak, diffuse Z pinch, spherical tokamak, and others) is also conceivable [3]. A possible way of solving the problem of a stand-off energy source has been delineated in Ref. [3], where it was suggested that the fusion reactor would work in the following way: the disposable assemblies (with the size of 30-50 cm) would be dropped into reaction chamber (whose walls would be protected by liquid Li or LiPb flow, very much like in ICF reactors, Ref. [4]), and the energy required to drive the implosion would be delivered from the distance of tens of meters (see below). It was assumed that the assembly would contain the following elements: i) the system for pre-forming the FRC (or other configuration to be adiabatically compressed); ii) the liner; iii) the on-board circuitry required to energize various systems in a required sequence (formation of pre-plasma, translation it into the liner, liner implosion).

To get some insight into the issue of what power supply systems may be needed, we consider creation of an FRC with the density n~10^{18} cm^{-3}, the temperature T~100 eV, in a magnetic field of B~100 kG. This set of parameters corresponds to

$$\beta \equiv \frac{16\pi nT}{B^2} \sim 1. \tag{1}$$

The radius of the FRC can be a~1 cm, and the length L~4-6 cm. Such an object could then be adiabatically compressed by an imploding liner (see Ref. [3] for a more detailed discussion and further references).

Magnetic coils of a radius $\sim 1.5a$ would be used for creating the bias magnetic field and for the field reversal. The bias coil can have a relatively long pulse, up to a hundred microseconds. The field-reversal coil should be turned on within a time of order of several axial Alfven transit times [5],

$$\tau = \alpha L / \mathrm{v}_A, \tag{2}$$

with α being of the order of 2. For the aforementioned set of parameters, and for a deuterium plasma, one has τ~ 1 μs. This estimate sets the time-scale for the controlled changes of the magnetic field.

The total energy content in the initial plasma will be ~ 1 kJ, and the magnetic energy will be several times higher, ~ 3 kJ (because the magnetic field occupies a larger volume). For τ~ 1 μs, the power level involved into the process of field reversal will be ~3 GW. The current in the coil,

$$I \sim \frac{cBL}{4\pi}, \tag{3}$$

should be $\sim 1.5 \cdot 10^{15}$ CGS~0.5 MA (for B~100 kG and L=6 cm). The required loop voltage will be of the order of 7.5 kV. All these parameters are not very demanding.

At the temperature of 100 eV, the plasma will be fully ionized, and its radiative losses will be [6]:

$$P_{rad}(W) = 1.7 \cdot 10^{-32} n^2(cm^{-3}) T^{1/2}(eV) \cdot \pi a^2(cm) L(cm) \tag{4}$$

For the parameters given above, this power will be only 2.5 MW, much less than the total power delivered to the plasma during the reconnection event, 1 kJ/1 μs ~ 1 GW. This means that radiative losses from a pure plasma are negligibly small. For radiative losses to become considerable, the plasma should become very dirty, with the amount of heavy impurities (of the type of iron) in the range of 1%.

The FRC with the aforementioned parameters will have a ratio of plasma radius to a characteristic ion gyro-radius of ~30-50, much higher than in the existing experiments and very close to the values of this parameter expected for an FRC-based fusion reactor [3]. The pre-formed FRC will be translated into an imploding liner of the type described in Ref. 3 and then adiabatically compressed. We conceive of a scenario where the on-axis hole through which the FRC will be injected will be closed early in the implosion, thereby trapping the FRC inside the liner. This can be achieved by using a liner whose linear density (mass per unit length) on the injection end is smaller than over the rest of its length (Cf. Ref. [7])

The compression should be 3-dimensional, because in 3D implosions the energy is delivered predominantly to the plasma, not to the embedded magnetic field [3]. The feasibility of quasi-spherical implosions has been demonstrated in the experiments by Degnan et al. [8]. In geometrically self-similar 3D implosions, the plasma temperature scales as

$$T = T_0 C^2 \tag{5}$$

where C is a linear convergence (the ratio of the initial dimension to the instantaneous dimension). If one starts with the plasma with the temperature T_0=100 eV, the fusion-grade plasma needs reaching C~7-10. Note that, in the aforementioned experiments by Degnan et al, the maximum linear convergence was close to 7. According to the analysis carried out in Ref. [3], the life-time of the hot dense state is determined by the liner expansion under the action of the plasma pressure. For the liners with a mass of a few grams, one can obtain the fusion gain Q ~ 10. The energy delivered to the liner should be in the range of a few MJ, with the characteristic time-scale of 1 μs [3].

There are several ways of delivering the energy to the assembly dropped into the reaction chamber. The one is to use an "inverse diode" system [3], where the assembly would be energized by a 1-MeV electron beam, penetrating into the assembly through the entrance foil, being absorbed by a cathode, and generating a voltage between the foil and the cathode. With an appropriate circuitry (including, possibly, a pulse transformer) installed in the assembly, this energy source could be used to drive some fast circuits. The second approach employs generating supra-thermal electrons by illuminating a kind of a thermoionic diode attached to the "assembly" by intense light of a low-quality CO_2 laser, and using these fast electrons to drive a current in the primary magnetic storage [9]. A third way is based on the use of fast flyers accelerated either electromagnetically (Ref. 10) or explosively (Ref. 11). These flyers could then be used to compress the conducting flux conserver enclosing some seed magnetic field (which could be generated, in particular, by the inverse diode system). The kinetic energy of the flyer would be converted into the magnetic energy and the latter would drive a circuit of the imploding liner. The flyers with velocities of order of 10^7 cm/s have been obtained in electromagnetic accelerators, with the flyer energy ~ 100 kJ [10]. Explosively driven cumulative jets with velocities up to $9 \cdot 10^6$ cm/s were also obtained [11]. Extrapolation to a few megajoules looks feasible, especially with explosively driven flyers. With a size of the flux conserver ~10 cm, one finds that a characteristic rise-time of the current generated by this magneto-compressive generator is ~ 1 μs, matching the natural time-scale of the problem. The magnetic energy in a magneto-compressive generator increases in the inverse proportion to the cross-sectional area. If the energy delivered to the liner has to be ~ 10 MJ, and the cross-sectional area is squeezed by a factor of 20, the energy content in the bias magnetic field has to be 0.5 MJ. This can be attained by creating a bias field of 20 T in a flux conserver of initial volume ~3 ℓ.

The fusion energy release inside the assembly will lead to its evaporation; the gas thus formed will be mixed with the LiPb gas formed because of evaporation of the protective liquid wall of the explosion chamber. To avoid the need in chemical separation of the mixture thus formed, it would be desirable to make the target of the same material as the liquid protective layer [12]. Both LiPb eutectic and a pure Li can be used as materials for the assemblies if cooled down to below minus 20 C. Some small amounts of other materials may still be needed in the assembly (to provide electrical insulation).

The practicality of this approach will depend not only on resolving a number of technical issues (which are quite challenging) but also on the possibility of mass-production of the assemblies (which would have to be delivered to the reaction chamber at a rate up to ten assemblies per second), and keeping their cost at the level of a few tens of cents per assembly. If the difficulties will prove insurmountable, one may consider systems with an increased yield (~200 MJ) and reduced rep rate (~1-2 Hz). In this latter case it may become feasible to use direct mechanical connections with the external power supply, in the style discussed some time ago [13]. What we would like to emphasize is that the whole system can be made of the LiPb (with some minimum amount of insulating materials). To reduce the weight and improve mechanical properties, one could consider using a porous LiPb (or even a pure Li) at a temperature in the range of minus 20 C. The density of this material, obviously, depends on its porosity and can be varied in a broad range. This circumstance allows one to tailor the density distribution around the point of the energy release in such a way as to produce significant hydrodynamic lensing [14], and direct the ejected material away from the most vulnerable elements of the reaction chamber.

To summarize the present status of the problem: Solutions that would allow to deliver the properly conditioned energy to the liner situated at a distance of ~10 m from the energy source, are feasible *in principle*. There is almost no doubts that one or even several of the aforementioned techniques can be realized in single-shot experiments. Main difficulties with the applications to a commercial generation of fusion energy are related to the feasibility of mass production of disposable elements at a low cost. It is desirable to direct some resources to the analysis of this problem.

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